ISSN 1028-3358, Doklady Physics, 2018, Vol. 63, No. 3, pp. 117–120. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © V.D. Sarychev, A.I. Nizovskii, A.A. Novikov, S.A. Nevskii, M.V. Trenikhin, A.Yu. Granovskii, V.E. Gromov, 2018, published in Doklady Akademii Nauk, 2018, Vol. 479, No. 3, pp. 00000–00000.

TECHNICAL PHYSICS

The Interaction Mechanism between Solid and Liquid Metals under Ultrasonic Action

V. D. Sarychev[a], A. I. Nizovskii[b,], A. A. Novikov[c], S. A. Nevskii[a,]*, M. V. Trenikhin[d], A. Yu. Granovskii[a], and V. E. Gromov[a]**

Presented by Academician V.I. Bukhtiyarov September 22, 2017

Received October 19, 2017

Abstract—At various structural-scale levels, the interaction between the aluminum alloy DT1 and a liquid eutectoid mixture of gallium and indium under the action of mechanical waves of the ultrasonic range is investigated. It is established that the deep penetration of the eutectoid mixture into the solid metal under ultrasonic action is due to the formation of channels along which the mixture moves. These channels are observed in both the axial and radial directions.

DOI: 10.1134/S1028335818030096

The phenomena arising under the interaction of solid and liquid metals has long attracted the attention of researchers in such fields as microelectronics, welding, and related technologies [1, 2]. At present, two types of interaction between liquid and solid metals are distinguished depending on the degree of solubility of the liquid in the solid [3]. At low solubility, liquid-metal embrittlement (the Rehbinder effect) is observed. At high solubility of the melt, plasticization of metal in the solid phase or intermetallide formation is observed. The principal mechanism of penetration of the liquid phase into a solid metal is diffusion along structural defects. The atoms of a surface-active liquid metal penetrating into a solid lead to a local decrease in the melting point of the material, liquid-phase formation, and, further, to nucleation and the development of a crack [4]. The ultrasonic action results in a sharp increase in the intensity of penetration of the liquid phase into the solid metal practically throughout the entire depth of the samples [5], which further leads to their damage. The diffusion penetration of liquid into the solid does not provide a full explanation for this phenomenon [6, 7]. The purpose of this study is to establish new experimental data and the mechanism of accelerated penetration (by two orders of magnitude higher than that under diffusion) of the liquid phase into the solid metal.

MATERIAL AND METHODS OF INVESTIGTION

As the object of investigation, we choose industrial aluminum alloy DT1, samples of which had a cylindrical shape. The dimensions of the samples were multiples of the length of the ultrasonic wave and represented the resonators of the ultrasonic radiator; the sample length was 120 mm, and the diameter was 20 mm. The samples were immersed in an eutectoid Ga–In (76 mass % Ga, t_{melt} = 15.9°C) mixture. As the

Table 1. Elemental analysis (in %) of the axial channels

Spectrum	Al	Cu	Ga	In	Total
2	0.88	0.66	1.05	97.41	100
3	89.73	0	9.62	0.66	100
4	92.24	3.74	4.02	0	100
5	92.90	3.84	2.19	1.06	100
6	72.18	2.54	0	25.27	100
Summary	89.65	4.49	3.44	2.42	100

[a] *Siberian State Industrial University, Novokuznetsk, 654007 Russia*
[b] *Boreskov Institute of Catalysis, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia*
[c] *Omsk State Technical University, Omsk, 644050 Russia*
[d] *Institute for Problems of Hydrocarbon Processing, Siberian Branch, Russian Academy of Sciences, Omsk, 644040 Russia*
**e-mail: nevskiy.sergei@yandex.ru*
***e-mail: alexniz@inbox.ru*

basic equipment, we used an ultrasonic generator and an ultrasonic-device radiator. The generated radiation frequency was 42 kHz. The amplitude of the vibrations of the working end face of the emitter and, consequently, of the end of the sample immersed in the eutectic was 10–12 μm. To investigate the structure of the material after processing, we used the methods of optical and scanning electron microscopy [8, 9].

RESULTS AND DISCUSSION

In Fig. 1, we show the optical images of the structure of aluminum alloy DT1 after combined treatment with a surfactant and ultrasound. From this figure, it follows that the ultrasonic processing results in the formation of two characteristic regions. In the first region, the ultrasonic action is strongest as indicated by the presence of dark inclusions. In the second region, there are no such inclusions, which enables us to conclude that, in this region, the ultrasonic action is minimal. The analysis of the cross-section image (Fig. 1a) showed that the inclusions have an elongated shape. Their transverse dimensions range from 20 to 100 μm, and the longitudinal ones range from 200 to 1700 μm. Apparently, the main element of these inclusions is the gallium–indium eutectic mixture. The analysis of Fig. 1 showed that the sizes of the inclusions range from 10 to 100 μm (Fig. 1b) and from 20 to 320 μm (Fig. 1c).

The results of scanning electron microscopy (Fig. 2) show that the dark inclusions observed using optical microscopy are nothing other than the channels through which the eutectoid mixture moves into the metal. This fact is illustrated by the results of X-ray spectral analysis. It is indium that mainly predominates in the axial (Fig. 2a) and radial (Fig. 2b) channels (Fig. 2a, Table 1, spectra 2 and 6, and Fig. 2b, Table 2, spectra 2, 5, and 8). In this case, the axial channels contain indium up to 97.41 mass %, whereas the radial channels have up to 40.00 mass %. The axial channels have transverse dimensions from 20 to 100 μm and radial ones from 0.5 to 1 μm. The formation of channels through which a liquid metal flows can be explained on the basis of the following considerations. In the absence of ultrasonic action, diffusion along the lattice defects, mainly along the grain boundaries, is predominant as was mentioned above [10]. The penetration rate of a liquid metal in this case is on the order of 1 μm/s [11]. Correspondingly, the time of this process can take about 24 h (Fig. 3a). Under ultrasonic-wave action, this effect increases by two orders of magnitude. As the experimental data have shown, channels can be formed outside the grain boundaries. To explain this fact, the following mechanism is proposed. As is known, under ultrasonic action with an intensity exceeding 1 W/cm^2 in a liquid, cavitation phenomenon occurs in it [12]. In this case, the liquid can rise to a height larger than that for ordinary capillarity. One of the mechanisms of this effect is the action of bubbles on the rise of the liquid in the capillary [13]. In our case, due to the motion of the bubbles, the flow of the eutectoid mixture is created (Fig. 3b). Its inflow onto the end of the channel wall provides the conditions for the reaction of the Al–eutectoid

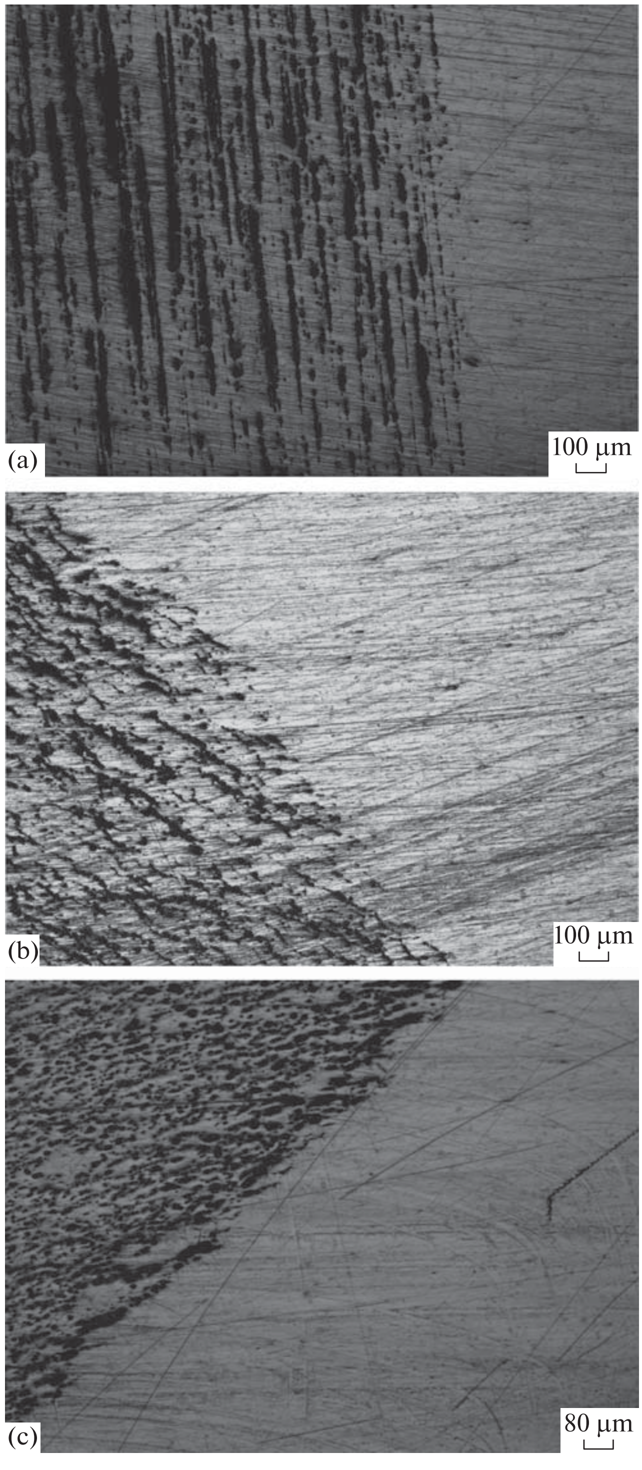

Fig. 1. Structure of aluminum after the action of surfactants and ultrasonic treatment (optical microscopy): (a) cross section; (b) longitudinal section (lower boundary of samples); (c) longitudinal section (upper boundary of samples).

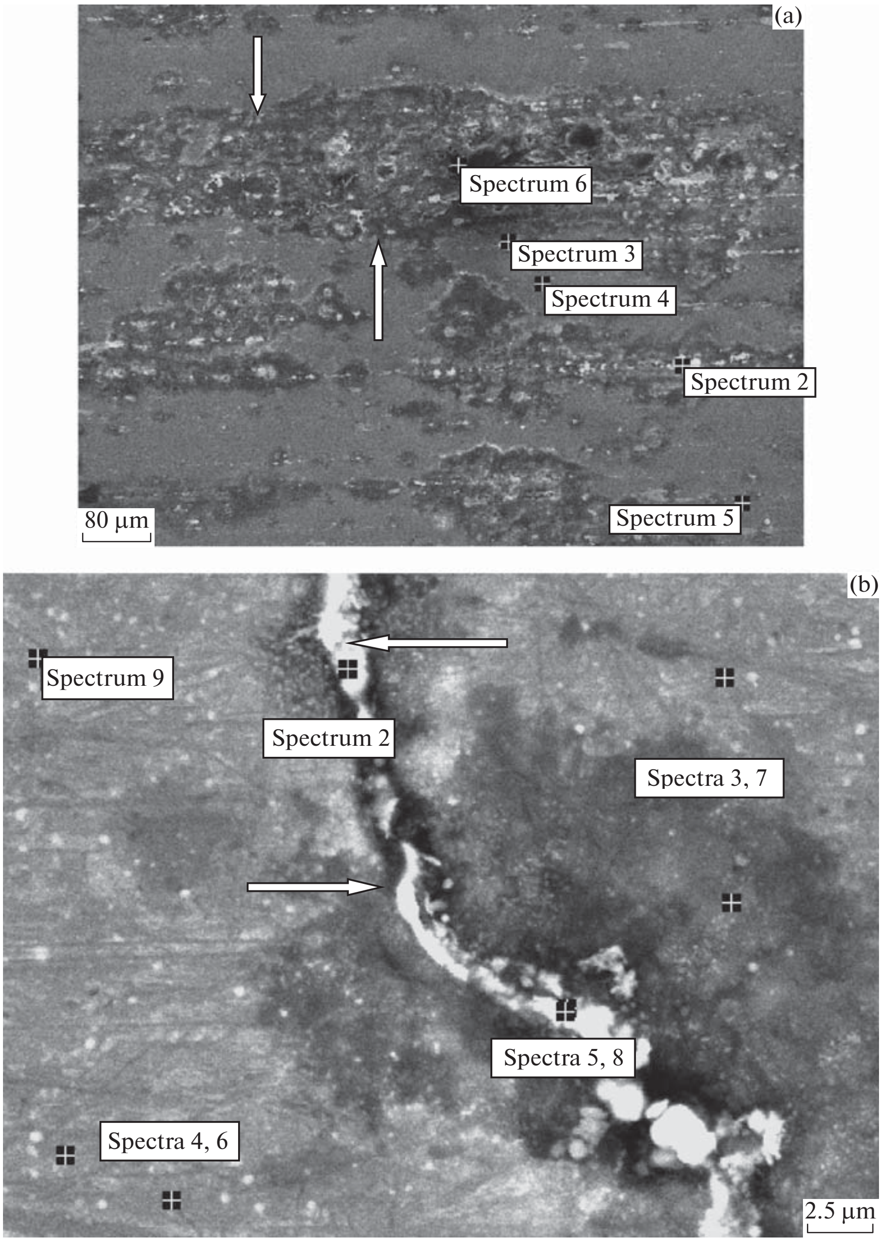

Fig. 2. Results of scanning electron microscopy of the DT1 alloy after the combined effect of the gallium–indium eutectoid mixture and ultrasound. The arrows indicate (a) axial channels and (b) radial channels.

mixture Ga + In. The end of the wall is corroded and, due to this fact, is displaced along the axis. It results in the formation of vertical channels (along the z axis). The radial channels arise due to branching of the vertical channel. The penetration of liquid metal into these channels is similar to the penetration of liquid into a horizontal crack in rock formations [14]. The estimate of the ultrasonic-wave pressure in the eutectoid mixture, according to [15], for the case described in this study showed that its value is 4 MPa for an ultrasonic-wave intensity on the order of 2.5 W/cm^2. These estimates confirm the existence of the channel-formation mechanism due to the cavitation of fluid bubbles.

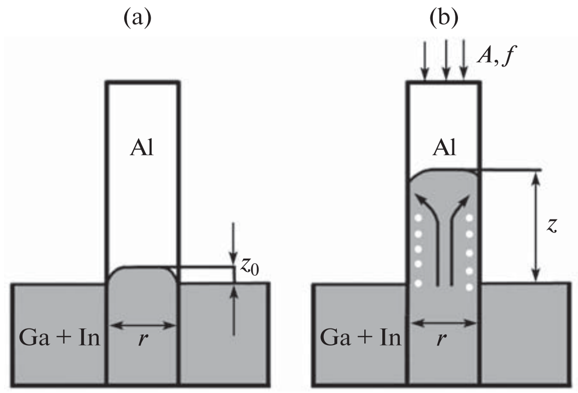

Fig. 3. Mechanism of formation of the axial channel: (a) without ultrasound; (b) with the action of ultrasound.

Table 2. Elemental analysis (in %) of the radial channels

Spectrum	C	O	Mg	Al	Cr	Cu	Ga	In	Total
2	17.67	18.35	0.84	23.79	0	3.94	4.48	30.92	100
3	20.22	0	0.75	74.93	0	3.08	1.02	0	100
4	21.34	2.14	0.77	73.16	0	2.60	0	0	100
5	24.31	17.83	0	13.15	0	2.49	2.23	40.00	100
6	28.67	17.29	0.67	50.38	0	2.18	0.81	0	100
7	13.75	1.72	0.91	78.95	0	3.23	1.44	0	100
8	20.71	17.99	0.58	13.01	2.54	1.49	1.81	41.87	100
9	0	0	1.09	94.17	0	4.74	0	0	100
Summary	18.38	10.75	0.81	62.97	0	2.96	1.43	2.70	100

Thus, in this study, we revealed the channels of the gallium–indium eutectic in aluminum, which do not coincide with the grain boundaries, and proposed a new mechanism for accelerated penetration of the liquid phase into the solid metal.

ACKNOWLEGMENTS

This study was supported by the Russian Science Foundation, project no. 15-19-00065.

REFERENCES

1. Yan Li, Yanhui Feng, Yafei Li, Xinxin Zhang, an Chuansong Wu, Int. J. Heat and Mass Transfer **92**, 628 (2016).
2. T. Vieira da Cunha and C. Enrique Niño Bohórquez, Ultrasonics **56**, 201 (2015).
3. V. I. Likhtman, E. D. Shukin, and P. A. Rebinder, *Physics and Chemistry Mechanics of Metals* (AS USSR Publishing, M., 1962) [in Russian].
4. A. P. Savitskii and L. S. Martsunova, Izv. Tomsk. Politekhn. Un–ta **315** (2), 123 (2009).
5. A. A. Novikov, A. I. Nizovskii, M. V. Trenikhin, and V. I. Bukhtiyarov, Mechanisms and Machine Sci. **23**, 309 (2014).
6. L. N. Larikov, E. A. Maksimenko, and V. I. Franchuk, Metallofizika **12** (1), 115 (1990).
7. M. N. Larichev, N. S. Shaitura, and O. O. Laricheva, Chem. Physics **27** (9), 95 (2008).
8. E. R. Clarke and C. N. Eberkhardt, *Microscopy Techniques for Material Science* (Woodhead Publishing, Cambridge, 2002).
9. M. M. Krishtal, I. S. Yasnikov, V. I. Polunin, et al., *Scanning Electron Microscopy and X-Ray Microanalysis in Examples of Practical Application* (Teknosphera, M. 2009) [in Russian].
10. O. V. Kozlova and A. O. Rodin, Poverkhnost No. 6, 42 (2005).
11. I. Tzanakis, W. W. Xu, D. G. Eskin, P. D. Lee, and N. Kotsovinos, Ultrason. Sonochem. **27**, 72 (2015).
12. P. P. Prokhorenko, N. V. Dezhkunov, and E. G. Konovalov, *Ultrasonic Capillarity Effect* (Navuka i tekhnika, Minsk, 1981) [in Russian].
13. M. G. Sirotyuk, *Acoustic cavitation* (Nauka, M., 2008) [in Russian].
14. V. N. Nikolaevskii, *Geomechanics. Collection of Works* (Izd. IKI, Izhevsk, M., 2010) [in Russian].
15. M. M. Iersel, N. E. Benes, and J. T. F. Keurentjes, Ultrason. Sonochem. **15**, 294 (2008).

Translated by V. Bukhanov

SPELL OK